

PROJECT ADMINISTRATION DATA SHEET

ORIGINAL



REVISION NO. _____

Project No. G-35-614

GTRI/614

DATE 3 / 20 / 84Project Director: Dr. R.E. HabermanSchool/~~dept~~ Geo SciSponsor: National Science FoundationWashington, DC 20550Type Agreement: Grant No. EAR-8407198Award Period: From 2/15/84 To 1/31/85 (Performance) 4/30/85 (Reports)

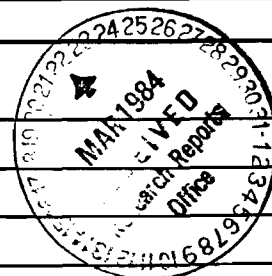
Sponsor Amount:

This ChangeTotal to DateEstimated: \$ _____ \$ 4,365Funded: \$ _____ \$ 4,365Cost Sharing Amount: \$ 437Cost Sharing No: G-35-319Title: "Asperity Recognition in Subduction Zones"ADMINISTRATIVE DATAOCA Contact Lynn Boyd x48201) Sponsor Technical Contact:Leonard E. JohnsonProgram DirectorSeismology and Deep Earth StructureNational Science FoundationWashington, DC 20550(202) 357-77212) Sponsor Admin/Contractual Matters:Lois A. Shapiro, Grants OfficerNational Science FoundationWashington, DC 20550(202) 357-9626Defense Priority Rating: n/aMilitary Security Classification: n/a(or) Company/Industrial Proprietary: n/aRESTRICTIONSSee Attached NSF Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of \$500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT.COMMENTS:COPIES TO:

I.D. No. 02.107.000.84.064

Project Director
Research Administrative Network
Research Property Management
AccountingProcurement/EES Supply Services
Research Security Services
✓ Reports Coordinator (OCA)
Research Communications (2)GTRI
Library
Project File
Other NEWTON

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 8/9/85

Project No. G-35-614

School/~~Lab~~ Geo Sci

Includes Subproject No.(s) _____

Project Director(s) Dr. R. E. Haberman

GTRC / ~~GIT~~ ^{XXXX}

Sponsor National Science Foundation

Title Asperity Recognition in Subduction Zones

Effective Completion Date: 1/31/85 (Performance) 4/30/85 (Reports)

Grant/Contract Closeout Actions Remaining:

- ☐ None
- ☐ Final Invoice or Final Fiscal Report
- ☐ Closing Documents
- ☒ ~~Final Report or Interim Report~~ Patent Questionnaire
- ☐ Govt. Property Inventory & Related Certificate
- ☐ Classified Material Certificate
- ☐ Other _____

Continues Project No. _____ Continued by Project No. _____

COPIES TO:

Project Director
Research Administrative Network
Research Property Management
Accounting
Procurement/GTRI Supply Services
Research Security Services
Reports Coordinator (OCA)
Legal Services

Library
GTRC
Research Communications (2)
Project File
Other A. Jones; M. Heyser

APPENDIX VI

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		FINAL PROJECT REPORT NSF FORM 984			
PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING					
PART I-PROJECT IDENTIFICATION INFORMATION					
1. Institution and Address Georgia Institute of Technology Atlanta, GA 30332	2. NSF Program Seismology and the Earth's Interior	3. NSF Award Number EAR-8407198 (transfer of EAR-8213083 to Ga. Tech frc U. of Colc			
	4. Award Period From 2/15/84 to 1/31/85	5. Cumulative Award Amount \$40,000			
6. Project Title Asperity Recognition in Subduction Zones					
PART II-SUMMARY OF COMPLETED PROJECT (FOR PUBLIC USE)					
<p>This project involved a global survey of seismicity levels in subduction zones using quantitative tools. The most important result of our work is the recognition that significant variations in levels of seismicity occur on a number of scales along most major subduction zones. This contrasts sharply with the general expectation of random or uniform spatial distributions of seismicity in these zones.</p> <p>We recognized a number of subduction zone segments with lengths of several thousand kilometers which have spatially consistent seismicity levels and are separated by sharp boundaries. The scale of these features and the sharpness of the boundaries suggests that they are tectonically controlled.</p> <p>Seismicity level variations with dimensions on the order of tens to hundreds of kilometers were recognized within the large-scale segments relative to the surrounding regions. However, each region we examined showed at least one small zone (<100 km) with extremely high seismicity. These zones appear to be active at all magnitude levels and, therefore, are probably important in the generation of large earthquakes.</p> <p>Our most detailed work on asperity recognition was done in the New Hebrides seismic zone. We found that regions which show many characteristics of asperities also showed high seismicity levels, suggesting that they were zones of stress concentration.</p>					
PART III-TECHNICAL INFORMATION (FOR PROGRAM MANAGEMENT USES)					
1. ITEM (Check appropriate blocks)	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM	
				Check (✓)	Approx. Date
a. Abstracts of Theses	X				
b. Publication Citations		X			
c. Data on Scientific Collaborators		X			
d. Information on Inventions	X				
e. Technical Description of Project and Results		X			
f. Other (specify)					
2. Principal Investigator/Project Director Name (Typed) Ray E. Habermann	Principal Investigator/Project Director Signature <i>[Signature]</i>			4. Date 7/19/85	

PART III -- TECHNICAL INFORMATION

a. Abstracts of Theses: None.

b. Publication Citations:

Wyss, M., R. E. Habermann, and Ch. Heiniger (1983). Seismic quiescence, stress drops, and asperities in the New Hebrides Arc, Bull. Seismol. Soc. Amer., v. 73, p. 219-236. [Copies attached.]

Habermann, R. E. (1984). Spatial seismicity variations and asperities in the New Hebrides seismic zone, J. Geophys. Res., v. 89, p. 5891-5903. [Copies attached.]

Wyss, M., R. E. Habermann, and J.-C. Griesser (1984). Seismic quiescence and asperities in the Tonga-Kermadec Arc, J. Geophys. Res., v. 89, p. 9293-9304. [Copies attached.]

Habermann, R. E., W. R. McCann, and B. Perin (in press, 1986). Spatial seismicity variations along convergent plate boundaries, Geophys. J. Roy. Astron. Soc., in press.

McCann, W. R., and R. E. Habermann (submitted). Morphologic and geologic effects of the subduction of bathymetric features, submitted to Tectonics.

c. Data on Scientific Collaborators:

Dr. W. R. McCann, Research Associate (Lamont-Doherty Geological Observatory, Columbia University, Palisades, NY)

Dr. Max Wyss, Professor (University of Colorado, Boulder, CO)

Ms. Barbara Perin, Student (University of Colorado, Boulder, CO)

d. Information on Inventions: None.

e. Technical Description of Project and Results:

This was covered in the proposal for a continuation of the project. Attached is a copy of the pertinent portion of that proposal.

TECHNICAL INFORMATION SUMMARY

OF PROPOSAL EAR-8407198

SUBMITTED AS PART OF PROPOSAL FOR CONTINUATION TITLED

"ASPERITY RECOGNITION IN SUBDUCTION ZONES"

INTRODUCTION

In this proposal we outline the work completed under NSF grant EAR-8213083 and propose to continue the work for one year. The primary goal of the first year of this project was the objective and quantitative recognition of spatial seismicity variations in subduction zones. We have achieved this goal in South America, Indonesia, the New Hebrides, Tonga-Kermadec, and Izu-Bonin-Marianas. The second phase of the work under grant EAR-8213083 was the examination of relationships between spatial seismicity variations and tectonic features. The initial stage of this work has been completed in the subduction zones listed above.

One might expect the seismicity distribution along plate boundaries to become more uniform as smaller events are considered. The results of the first year of this work clearly indicate that this is not true, at least for the magnitude levels we considered ($m_b > 4.8$ to 5.5). We recognized variations in background seismicity on two different scales, thousands of kilometers and tens of kilometers. The larger scale variations must be tectonic in origin because of the scale involved. The shorter scale variations could be related to asperities on the interface or to tectonic features (these cases may not be mutually exclusive).

The significance of these variations was evaluated in two ways. First, the seismicity rates in neighboring regions were compared using the z-test for a difference between two means. All of the regions we list below showed mean differences significant at the 99%+ level. Second, we determined the probabilities of generating the observed variations in stationary Poisson processes. This test confirmed the 99%+ significance of more than 70% of the observed variations. These results demonstrate that the spatial distribution of seismicity along convergent plate boundaries is **not random**.

We are interested in recognizing spatial seismicity variations because of their possible relationship to asperity distributions on plate interfaces. This is important for understanding the role of asperities in the generation of large earthquakes and crucial for the prediction of these events. We have shown that the asperities in the New Hebrides are regions of anomalously high seismicity. In addition, we have shown for the first time that asperities in subduction zones can be directly related to bathymetric features on the seafloor. These exciting results bode well for the role of careful seismicity studies in asperity recognition. However; we found that, in general, there are more large events than there are regions of outstanding seismicity. If each large event originates in an asperity, this implies that only a portion of the asperity population can be recognized using background seismicity.

We found a large number of seismicity variations which are spatially related to tectonic features on the seafloor or the overriding plate, suggesting that tectonic features play a major role in controlling background seismicity.

In the process of searching for bathymetric features related to observed seismicity variations we noticed that such features have a profound effect on subduction zone morphology. This effect can be observed in trench and forearc sediments and even in the overriding plate. While other authors have discussed this effect locally, the global nature of our study allowed us to integrate many of the local cases into a model which describes a full spectrum of effects.

The observations made during the first year of this project indicate that variations in background seismicity provide a powerful tool for characterizing subduction zones. In this proposal we seek funds for completing our global

study of seismicity variations along convergent boundaries. We also propose a detailed study of small zones of extremely high seismicity which we discovered during the first year of this work. Finally, we will study aftershock sequences in addition to background seismicity for evidence of asperities.

PREVIOUS WORK

The work we have completed during the first year of this project falls into two categories. First, the recognition of spatial seismicity variations in subduction zones and second, the recognition of effects of bathymetric features on subduction zone morphology. In this section we will discuss the techniques used and the major findings of our work completed to date.

Spatial Seismicity Variations in Subduction Zones

During the first year of this project we examined subduction zones in South America, Izu-Bonin-Marianas, the New Hebrides, Tonga-Kermadec, and Indonesia. In each of these regions we completed the following five steps: 1) Determined the minimum magnitude of homogeneous reporting; 2) Identified aftershocks of all events with $M_S > 6.0$; 3) Recognized large scale (1000+ km) background seismicity variations (first-order segments); 4) Recognized small regions (<100 km) of extremely high seismicity (first-order actives); 5) Recognized 10-300 km regions of anomalously high or low seismicity within the first-order segments (regions of outstanding seismicity). In the New Hebrides we have completed a quantitative evaluation of the relationship between zones of outstanding seismicity and asperities (see discussion below).

In some of these regions we have made progress in identifying relationships between spatial seismicity variations and tectonic features. In this section we will summarize those steps and present the conclusions we have reached.

1) DETERMINING THE MINIMUM MAGNITUDE OF HOMOGENEOUS REPORTING

Temporal variations in teleseismic detection have occurred in many regions of the world since 1963 (Habermann 1982a). We determined the minimum magnitudes of homogeneous reporting for all regions we studied using the techniques described by Habermann (1983). We used magnitude cutoffs which eliminated events which had not been consistently reported. In this way, we avoided any problems which inconsistent reporting might cause in spatial studies. The subduction zone segments and the minimum magnitudes of homogeneous reporting which we determined are listed in Table 1.

2) RECOGNITION OF AFTERSHOCKS

The statistical approaches we used in this work depend on the assumption that the events we considered were independent. A major step towards satisfying this assumption was made by recognizing aftershocks of all events with $M_S > 6.0$. We did this through individual examination of each of these mainshocks and the events which followed them over several months to a year. In addition to satisfying the assumption, this step provided great insight into characteristics of aftershock sequences, as several hundred were examined individually.

3) RECOGNITION OF LARGE SCALE CHANGES IN BACKGROUND SEISMICITY LEVELS

We examined the question of whether background seismicity levels were consistent along entire subduction zones, and found that they were not.

We used an algorithm described by Habermann (1983) to identify large scale (1000+ km) segments of subduction zones with consistent background seismicity rates. We term these first-order segments. The levels of background activity in neighboring segments were different at the 99%+ confidence level in all cases. Three such segments were found in South America, Indonesia, and in the Izu-Bonin-Marianas, two in the New Hebrides, and one in the Tonga-Kermadec.

In some cases the boundaries determined from background seismicity levels coincided with well documented tectonic boundaries, in others they did not. The segments we found, the seismicity rates and tectonic character of these segments, and the known tectonic features at their boundaries are listed in Table 2.

In addition to making the quantitative recognition of these first-order segments possible, this step insured that the subduction zone segments which we examined for second-order variations had spatially consistent background rates.

4) RECOGNITION OF FIRST-ORDER ACTIVE REGIONS.

In all of the subduction zones which we examined we found small regions (< 100 km) with extremely high seismicity levels. We term these regions first-order actives. Most of these active areas are active at all magnitude levels, and some appear to play an important role in the generation of great earthquakes. The first-order actives which we recognized are listed in Table 3.

Explanations for some of the first-order active regions are clear. For instance, the active regions at the northern ends of the New Hebrides and Tonga arcs are probably related to sharp bends in the plate boundaries. Other explanations are more speculative. The active area at the southern end of Sumatra may be related to the subduction of sediment filled troughs and the active area in southern Chile may be related to the subduction of a relic spreading center (as discussed below).

The first-order actives appear to be important in the generation of large earthquakes. The most dramatic example of this is the Mocha block in Chile. The great foreshocks and the mainshock of the 1960 Chile earthquake occurred in this zone. This zone was also active during the time prior to the 1960 event (Perez, 1983). Another great earthquake occurred there during 1975 ($M_s = 7.8$). The record of large earthquakes during this century indicates the repeat time for $M=7$ events in the Mocha block is 14 years, a factor of ten shorter than the estimated repeat time for the 1960 Chile event (Nishenko, JGR, in press). The historic record (1756 to present) in Indonesia also indicates that the first-order active zone off of southern Sumatra has experienced many large events relative to the surrounding regions (Newcomb and McCann, JGR, submitted). These observations indicate that the first-order actives are active at all magnitude levels, not just for smaller events which we used to recognize them.

In addition to making the quantitative recognition of these first-order actives possible, this step prevented the introduction of large standard deviations into the background rates, thus making the recognition of second-order variations possible.

5) RECOGNITION OF SECOND-ORDER SEISMICITY VARIATIONS.

After the steps outlined above have been completed, we can recognize the smaller scale seismicity variations which are the main target of this work. This was done using a technique described by Habermann (1984, see Appendix I) which recognizes regions within the subduction zones in which the seismicity level is significantly different than the regional background level. These regions are identified by comparing the seismicity rates (eq/km) in all sections of the subduction zones with the regional background rates determined in step 3 above. We did this for sections ranging in length from 20 to 200 km. The comparisons were done using the z test for a difference between two means. In this way the significance of the difference between the local rates and the regional rates could be determined and all variations above a given level of significance could be objectively recognized. We accepted only differences which were significant at the 99%+ level.

After the regions of outstanding seismicity were recognized using the z test, we determined the probabilities of observing the regions in stationary Poisson sequences. This second statistical approach confirmed the 99%+ significance of these anomalous regions in over 70% of the cases. Only one of the 63 regions recognized was not significant at the 95%+ confidence level.

Table 4 lists the regions of outstanding seismicity which we have recognized. The locations are given in our coordinate systems (km) as well as in latitude and longitude. The lengths of the regions (L) in km are also shown. The z values in Table 4 result from comparing the spatial seismicity rate in the region of outstanding seismicity to the rate in the first-order segment which contains the region using the z test for a difference between two means. Positive z values indicate that the region has low seismicity and negative z values indicate that the region has high seismicity. The z values have the same statistical interpretation as the number of standard deviations from the mean of a normal distribution, i.e., $z = 1.95 = 95\%$, $z = 2.57 = 99\%$, so a region with a z value of 5 would occur as often as a data point five standard deviations from the mean in a normal distribution. Stat lists the probabilities of not finding these regions if the spatial distribution of background seismicity was Poisson. In this section we will focus on several variations which represent general findings.

Eight of sixteen quiet zones recognized in South America are spatially associated with known fracture zones. At least four of these are located on the old sides of the fracture zones. This is particularly clear in the southernmost segment of South America where the fracture zones are well known because of their association with the presently active East Pacific Rise. North of 38°S the fracture zones which are presently interacting with the subduction zone were formed at the now inactive Pacific-Farallon spreading center and are less well known.

Figure 1 shows the seismicity of the southernmost first-order segment of South America. The quiet regions near 42° and 44°S are on the old sides of Fracture Zone 43 (FZ 43) and the Gualafranca Fracture Zone (GFZ). These quiet regions are both significant at the 99%+ level according to the z test, and at the 98% and 99% levels according to the stationary Poisson test. The quiet region near 35°S is not associated with a known fracture zone.

The observation that the old sides of fracture zones are quiet might be qualitatively understood if one considers the geometry of such zones. These zones separate seafloor of different ages and, therefore, different depths. The younger seafloor is less dense and higher than the older, thus the fracture zones are step functions in the bathymetry. This geometry is shown in

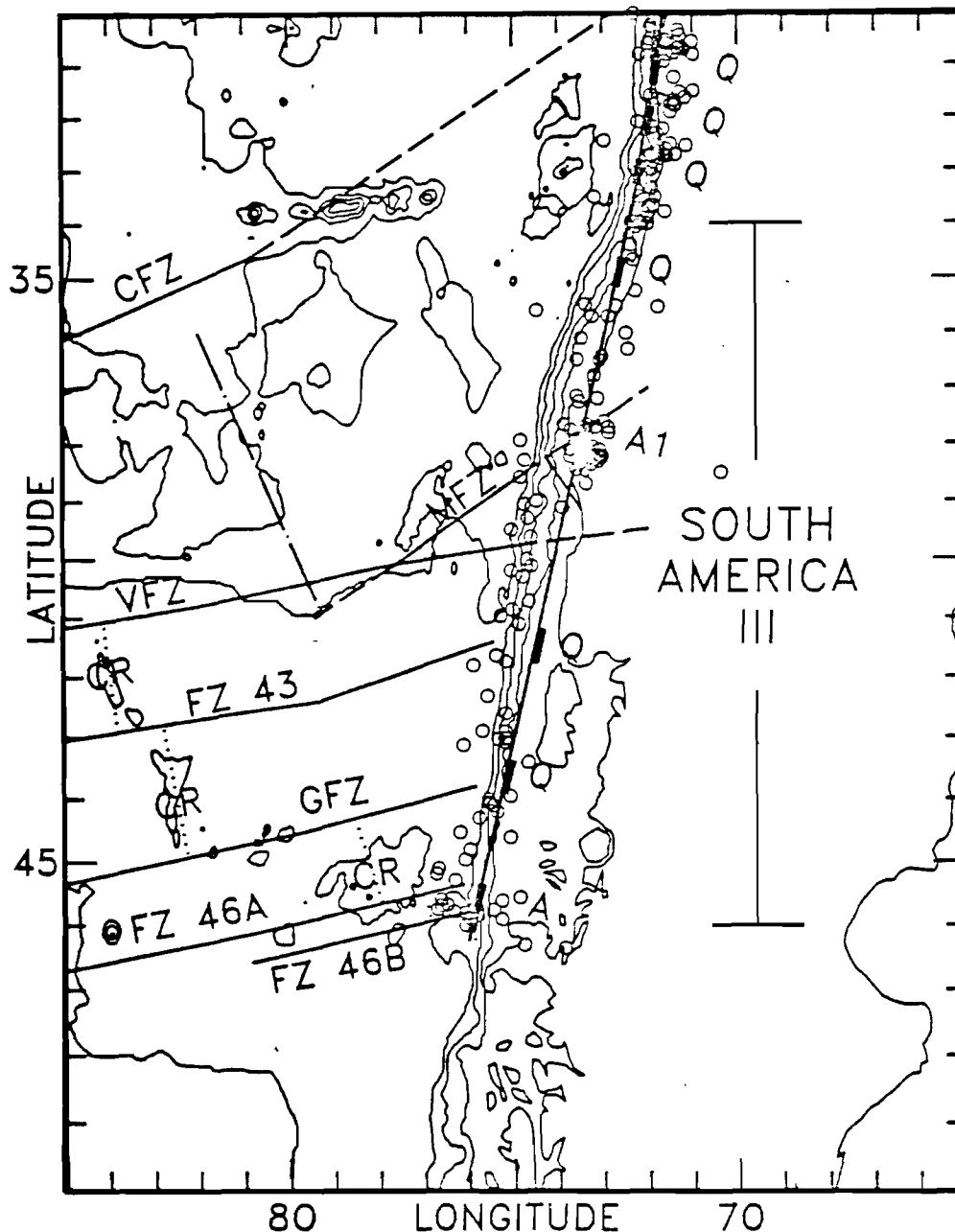


Figure 1. Map of southern Chile showing the seismicity we considered (circles), the axis of the coordinate system (long solid line), the areas with anomalously high (A) or low (Q) seismicity (thick line segments), and the major features of the seafloor. Note the quiet areas near 42° and 44° S which are spatially associated with Fracture Zone 43 (FZ 43) and the Guafo Fracture Zone (GFZ). Also note the extremely active region near 38° S which is surrounded by the Mocha and Valdivia fracture zones.

Figure 2A with the older seafloor on the left. The shaded area in Figure 2A represents a "shadow" of the fracture zone. Such "shadows" may be zones of decreased normal stress across the plate interface or of increased sediment subduction, both of which might enhance the possibility of aseismic motion between the plates and hence decreased seismicity.

A similar effect might be expected around aseismic ridges on the seafloor. This example is illustrated in Figure 2B. Here the effect would be symmetrical, in contrast to the fracture zone case. We observed symmetric effects in Indonesia, South America, and the Marianas.

The Investigator Ridge is a feature on the floor of the Indian Ocean with up to 2 km of relief (Moore et al., 1980). It strikes nearly north-south and is located near 98.2°E (Figure 3). The orientation of this feature relative to Sumatra results in an interaction zone which extends from 3°S to 1°N. Figure 3 shows the seismicity of this region which we considered (1963 to May 1981, $m_b > 5.5$, events on the interface). Two quiet regions (Q's in Figure 3) surround the zone of interaction between the Investigator ridge and the Sumatra subduction zone. This is the effect expected on the basis of the qualitative model suggested in Figure 2B. These quiet areas are both significant at well above the 99% level according to the z test (z in Table 4), and at the 98% and 99% levels using a stationary Poisson test (Stat in Table 4). In other words, these quiet areas would be observed less than 2% of the time if the background seismicity in this segment were random.

The examples we have presented so far show effects of features on the seafloor on the seismicity levels on the interface. Such effects are expected because the seafloor features directly affect the interface geometry. The Izu-Bonin-Marianas subduction zone presents a case which confounds one looking for such interactions. The cumulative number of events as a function of distance along this subduction zone are shown in Figure 4. The first-order segments listed for this zone in Table 2 are apparent in this Figure. Note the choppy character of the seismicity in segment I between 27.7° and 35°N. This contrasts strongly with the smooth character of the seismicity in segment II between 14.7° and 27.7°N. If one believed that this seismicity was controlled by seafloor features, one would expect rough bathymetry off of segment I and smooth seafloor off of segment II. What one observes, however, is the opposite. The seafloor off of segment I is almost featureless, while the seafloor off of segment II contains numerous seamounts.

This example indicates that one must also examine the overriding plate for variations which might relate to seismicity variations. The recent discovery of cross-arc volcanic chains behind the Izu-Bonin-Marianas subduction zone (Hussong and Fryer, 1983) may provide a solution to the paradox outlined above. The possibility that these chains affect the seismicity on the interface is suggested by the fact that the chain discussed by Hussong and Fryer strikes into one of the quiet regions we recognized in the northern Marianas.

CONCLUSIONS ABOUT SPATIAL SEISMICITY VARIATIONS

In this section we have briefly described the techniques we developed and used in this project and have listed some of the interesting observations we have made. The major conclusions about spatial seismicity variations are: 1) Background seismicity is not randomly distributed along convergent plate boundaries. Significant variations were identified on scales of tens and thousands of kilometers. 2) With the exception of a few areas with extremely high activity, subduction zones can be characterized by areas of normal seismicity separated by areas of low seismicity. The areas of high seismicity

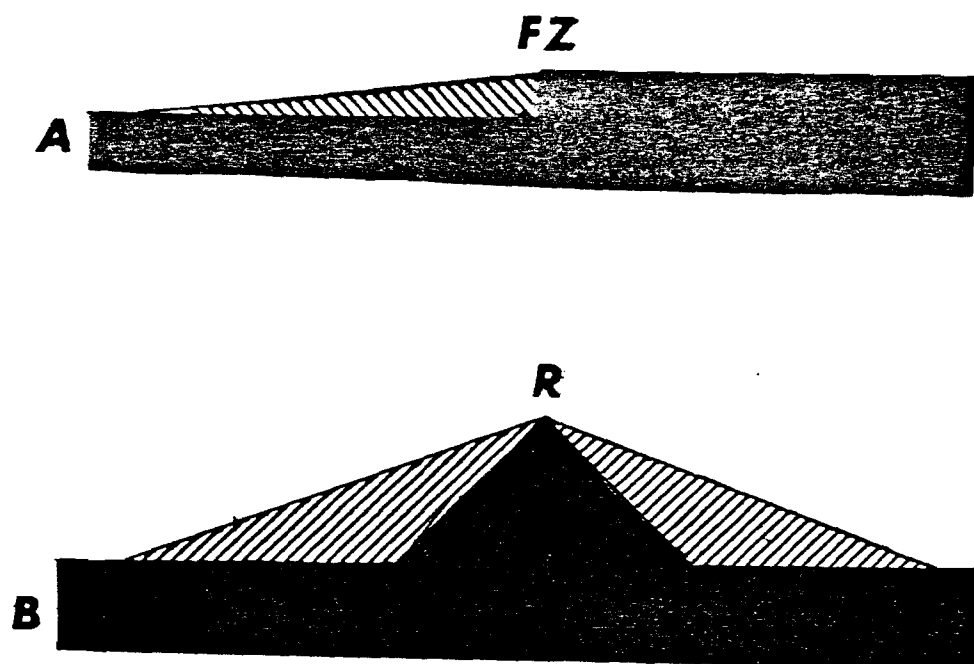


Figure 2. Schematic illustration of the mechanism which may cause low seismicity on the old sides of fracture zones (A) and around ridges (B). The shapes of the seafloor at these features are shown and the shaded zones are zones of low normal stress or enhanced sediment subduction, both of which might increase the role of aseismic processes and decrease the amount of background seismicity expected.

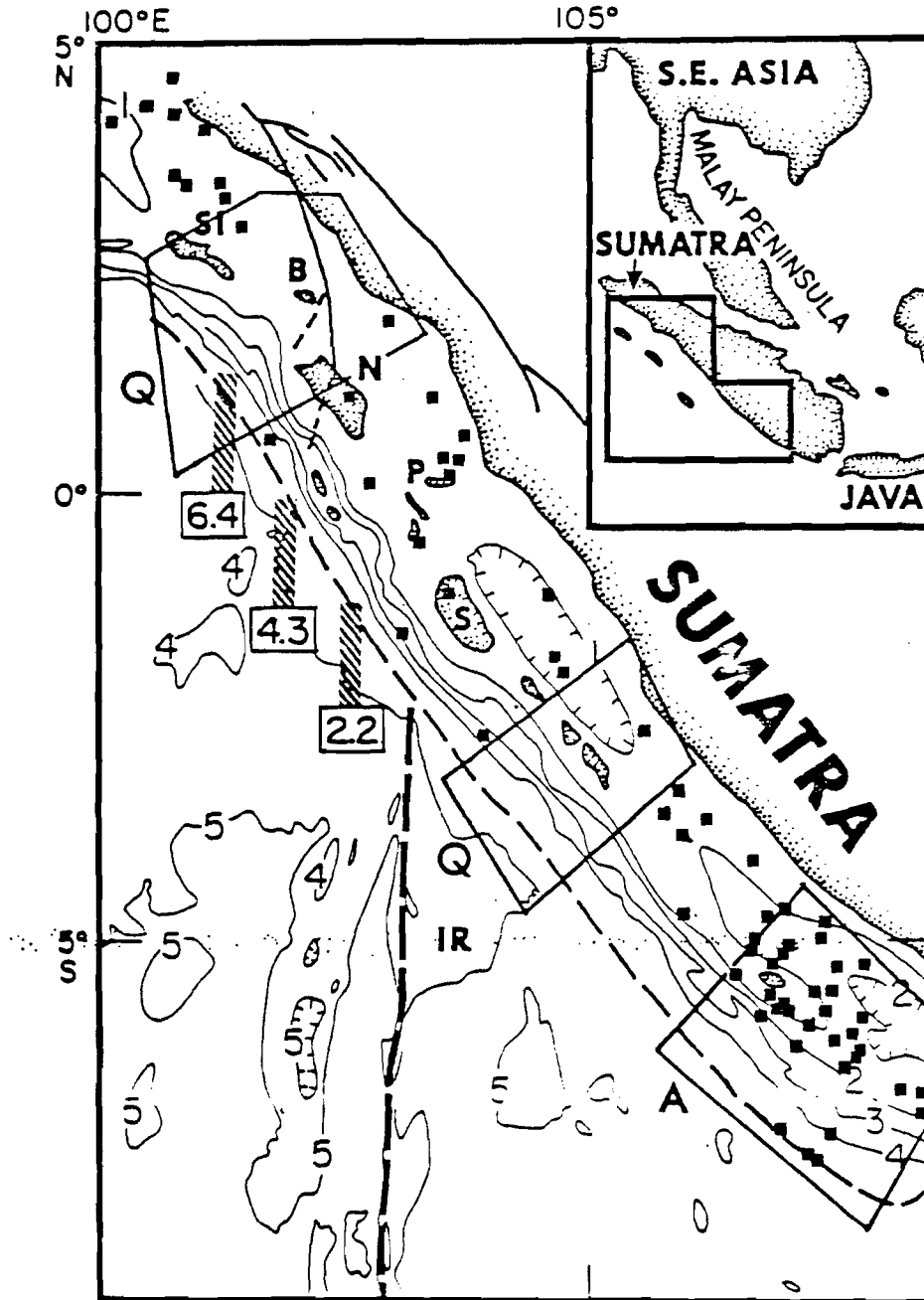


Figure 3.

Figure 3. Map of Sumatra showing the seismicity we considered (solid squares), and the location of the Investigator Ridge (IR). Note the existence of two quiet regions (Q's) surrounding the ridge. This is the effect expected on the basis of the qualitative model pictured in Figure 2. The region of high activity at the southern end of Sumatra (A) may be caused by subduction of sediment filled troughs located on the seafloor outside of this zone.

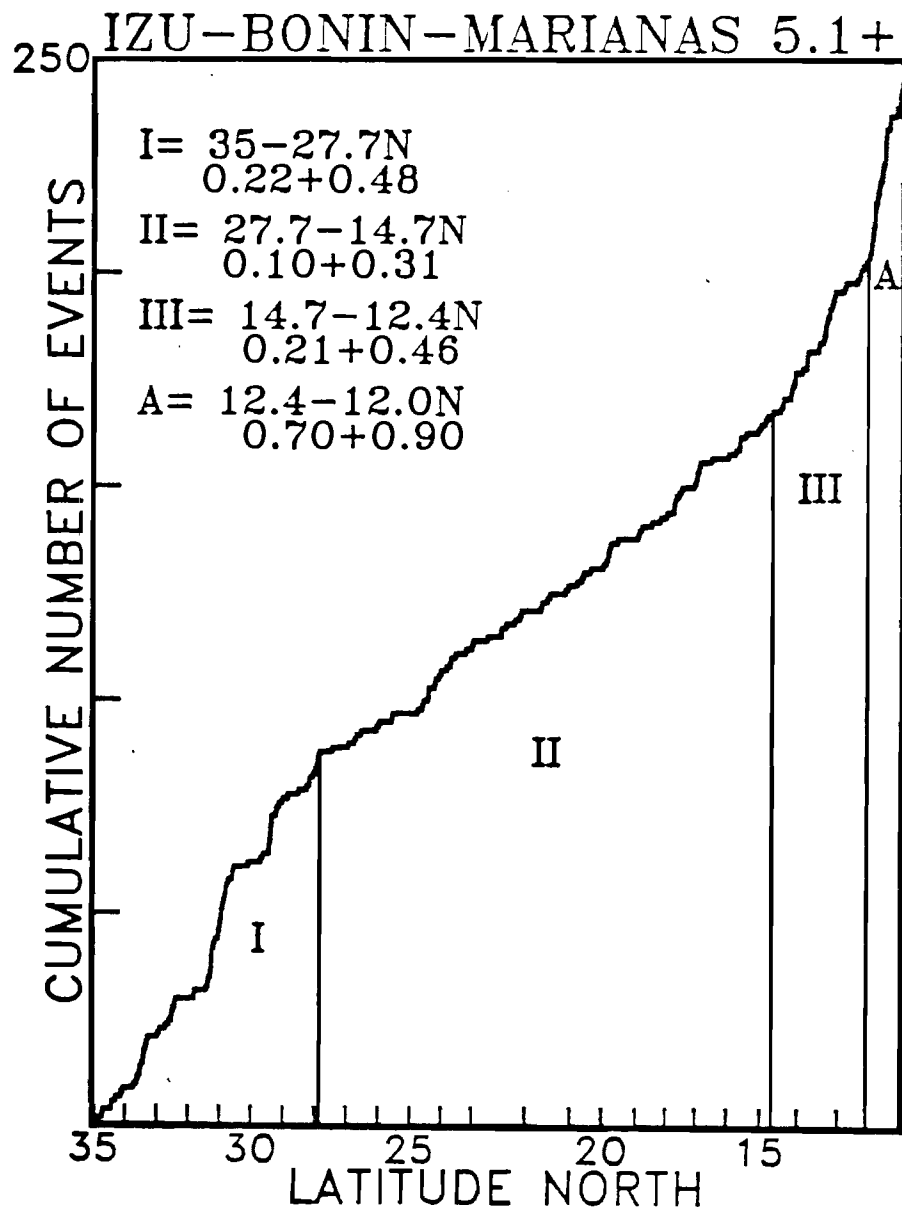


Figure 4. Cumulative number of events as a function of distance from north to south along the Izu-Bonin-Marianas subduction zone. Aftershocks, non-interface events, and events which have not been consistently reported through time are removed. The three first-order segments and the first-order active region which we identified are clear in this figure and are labeled I, II, III, and A. Note the difference between the character of the seismicity in segments I and II. Segment I shows very choppy seismicity with either many or few events occurring. Segment II, in contrast, shows a very consistent seismicity rate along its entire length.

generally are anomalously active at all magnitude levels. 3) In many cases, background seismicity variations appear to be controlled by tectonic features. 4) Areas of low seismicity tend to occur on the old sides of fracture zones and flanking aseismic ridges that have entered the subduction zone. 5) Features on the seafloor as well as on the overriding plate can affect interface seismicity.

Geologic and Morphologic Effects of Subduction of Bathymetric Features

We have investigated over 20 examples of changes in subduction zone geology and morphology associated with the subduction of aseismic ridges and other bathymetric features. Our observations suggest that two factors control the effect of bathymetric features on subduction zone morphology, the relief of the bathymetric feature and the type of compensation. Uncompensated, small-scale features, like many fracture zones, affect primarily the sediments in the forearc. Large, compensated features, on the other hand, can have observable effects well into the overriding plate. In this section we present examples which demonstrate the variation in morphological effects we observed.

An example of the effect of bathymetric features on trench morphology occurs where the Louisville Ridge enters the Tonga-Kermadec trench (Figure 5). This Figure clearly demonstrates two effects. First, the trench axis is deflected landward, and second, the inner wall in the region which the Louisville Ridge has passed through is steepened. These observations are consistent with a model in which the relief of the Louisville Ridge has compressed sediments and thrust them against the inner wall of the trench.

An example which demonstrates effects on the forearc ridge is the Investigator Ridge in the Sumatra trench (Figure 3). The history of three islands in the Sumatran forearc (Banyak, Nias, and Siberut) show a southward migrating compressional pulse starting five million years ago at Banyak and continuing today at Siberut. This pulse manifested itself by two km of reverse faulting which uplifted the Banyak Islands, uplifting and landward thrusting of Nias island, and compressional tectonics near Siberut (Karig et al., 1980). The times and positions of the observed deformations are coincident with the migration of the Investigator Ridge southward along the arc.

An example of the effects of the subduction of a compensated feature can be found in the South American subduction zone. During the last 10 million years the Nazca Ridge has passed beneath the Lima Basin, a large structural depression on the Peruvian shelf. This basin has subsided by up to 1100 meters during the last 5 million years. The spatial and temporal coincidence of this massive subsidence and the passage of the Nazca Ridge suggests that they are related. Perhaps this subsidence reflects tectonic erosion of the South American margin by the Nazca Ridge. Such erosion probably occurs only during the subduction of compensated features, because of the buoyancy of these features, and the resulting strong interplate coupling.

Other results of this investigation are presented in Tables 5 and 6, and a cross section depicting our observations in a hypothetical subduction zone is shown in Figure 6. All morpho-geologic changes are not observed in one subduction zone because of the structural variation of converging plates and the many geometries possible in ridge-trench interactions.

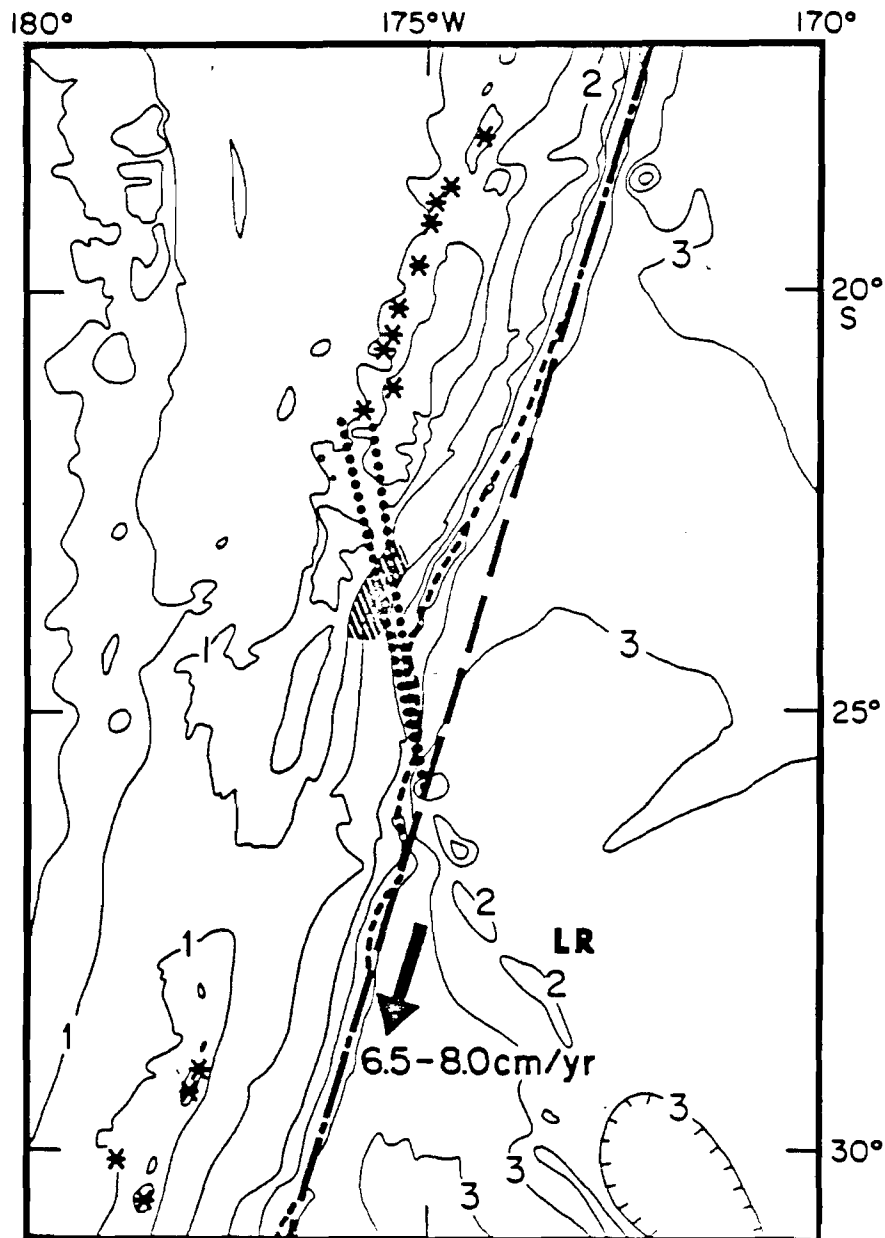


Figure 5. Displacement of the Tonga trench by subduction of the Louisville Ridge (LR). Note how the trench axis (small dashed line) is positioned abruptly landward of its average position (dashed line) along the southern Tonga and Northern Kermadec arcs. Displacement is largest immediately to the north (i.e. in the wake) of the Louisville Ridge and gradually decreases to the north. Intersection of ridge and trench migrates to the south at about 6.5 to 8 cm/yr. The distance between the 1000 and 3000 fathom contours is smallest (hatched) near the intersection, indicating a steepened inner wall. Asterisks are sub-aerial, Quaternary volcanoes. Approximate map-view extension of Louisville ridge into the subduction zone is shown by a pair of dotted lines.

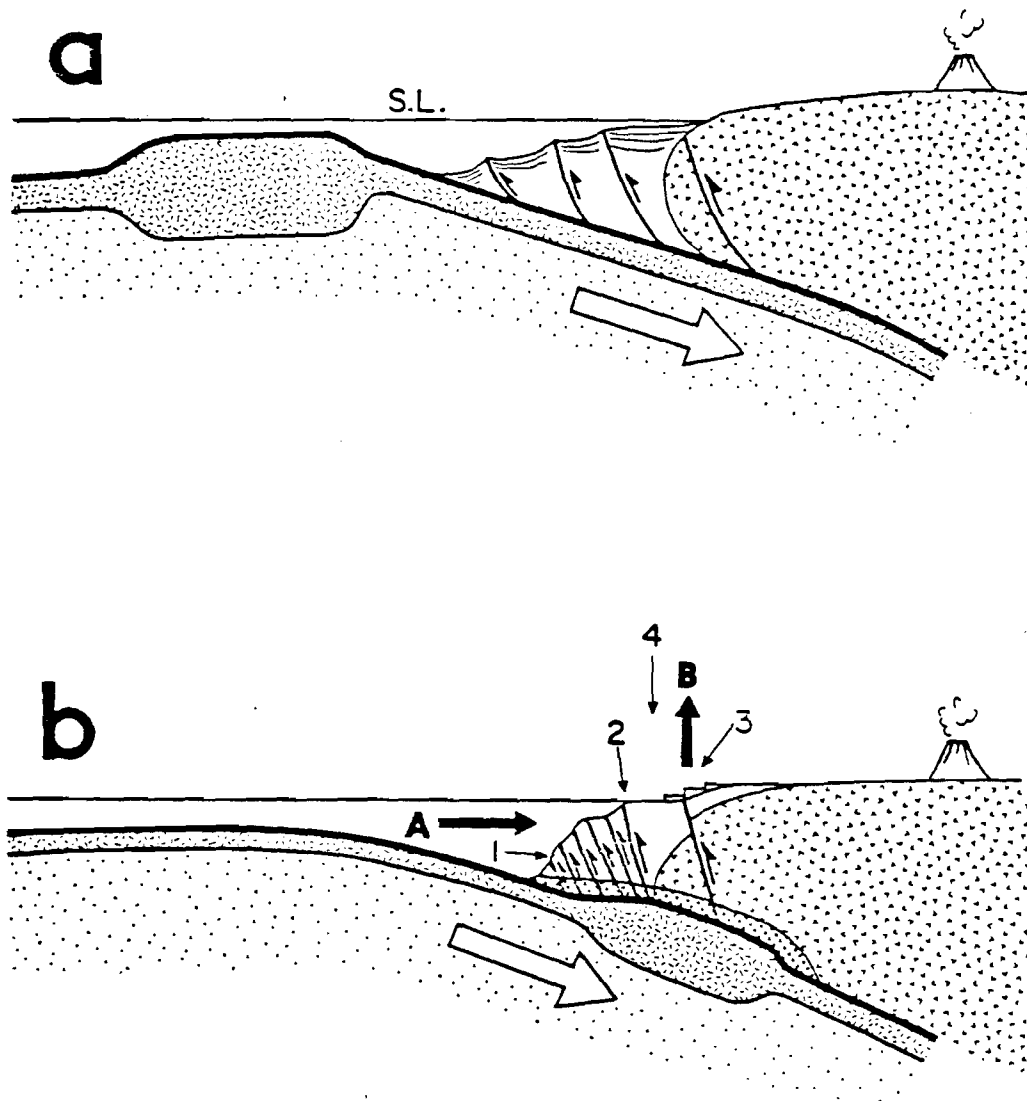


Figure 6. Cross section of effects of ridge subduction. a) Subduction zone in quasi-equilibrium state as ridge approaches trench. b) Possible effects of subduction of aseismic ridge: 1 - steepened inner wall of trench resulting from snowplowing of accretionary prism, 2 - deformation of sediments in accretionary prism by folding and/or thrusting, 3 - development of coastal terraces as upper plate readjusts to relief of downgoing plate, 4 - massive subsidence occurs if tectonic erosion at base of overriding plate occurs. S.L. is sea level, A represents compressive forces exerted on overriding plate by relief of ridge, B represents vertical forces related to buoyancy of downgoing ridge, open dot pattern in (b) is possible region of tectonic erosion.

Relationship Between Seismicity Variations and Asperities

Asperities are important in controlling earthquake ruptures and the nature of precursory patterns. Therefore, correct identification and meaningful evaluation of precursory seismicity patterns as well as the prediction of important characteristics of upcoming events hinge upon understanding the asperity distribution in which these events are occurring. Recognizing this distribution using waveform studies after the mainshock occurs certainly contributes to understanding these events, however, for earthquake prediction such recognition is a classic case of closing the barn door after the horse has left. We must develop the capability to infer the asperity distribution using evidence which exists prior to the mainshocks if we are to achieve realistic earthquake prediction. Contributing to that capability is a major goal of this study.

In this section we integrate observations of background seismicity variations with other seismological evidence for asperity existence. We demonstrate a broad approach to asperity identification and indicate the role of background seismicity in that approach. The results we show demonstrate the potential of careful studies of background seismicity for asperity recognition.

THE NEW HEBRIDES

The level of background seismicity expected in asperities on fault interfaces is unclear. They may appear as quiet zones because of high strength or active zones because of high stress. We have addressed this problem by identifying zones of anomalously high or low seismicity and comparing the locations of these regions with the locations of asperities as determined from other observations. The characteristics we used for asperity recognition are listed in Table 7 for two possible stages during the cycle of an asperity. The strength dominant stage occurs early in the cycle, when the stress is well below the strength. The stress dominant stage occurs later, after the stress has increased to near the strength of the asperity.

A number of regions which show some of these characteristics were identified in the New Hebrides (Habermann, 1984, Appendix I). We also know the locations of regions of outstanding seismicity in the New Hebrides (Table 4), so we can evaluate whether the observed relationship between these two types of regions would occur by chance. This is done by assuming that the types of regions are independent and comparing the expected and observed overlaps between the sets. In order to do this we must know the portion of the seismic zone which is covered by each type of region. The active regions make up 10%, the quiet zones 16%, leaving 74% of the seismic zone with normal seismicity levels. This distribution is shown in the upper part of Figure 7. The asperities (which were recognized independently from their seismicity levels) make up 34% of the seismic zone.

If the quiet regions were randomly distributed, we would expect 34% of the quiet regions to be in asperities. The observed percentage is 9%. The relationship between the quiet areas and the asperities, therefore, does not appear to be random. In fact, it appears that the quiet regions occur preferentially outside of regions with other asperity characteristics.

If the active areas were randomly sampled from the arc, we would expect 34% of the regions to be in asperities. In fact 100% of the active areas occur in regions with other asperity characteristics. This indicates that the active areas occur preferentially in areas with other asperity characteristics.

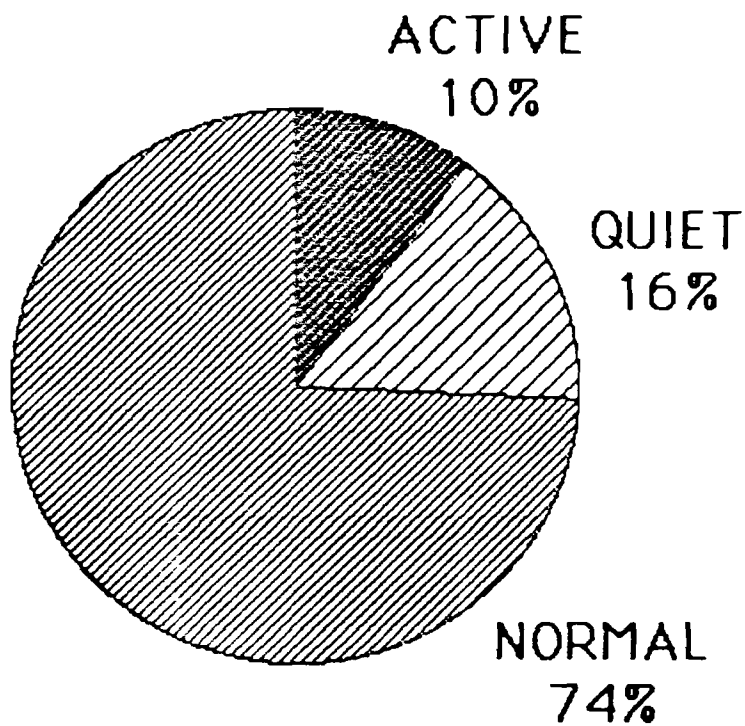
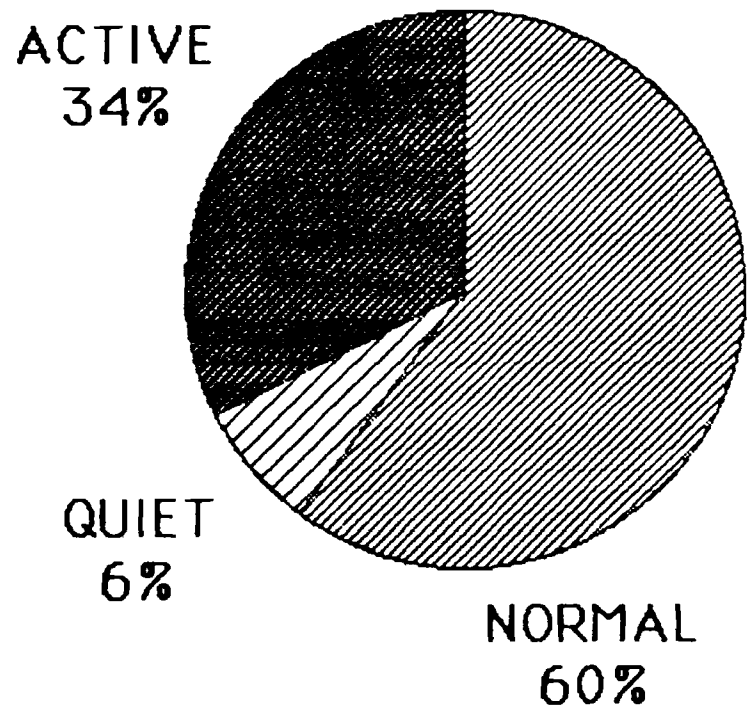


Figure 7.
This shows the distribution of active and quiet areas in the New Hebrides seismic zone. This, therefore, is the expected distribution for any randomly selected subset of the seismic zone.

This is the distribution of active and quiet areas in the asperities in the New Hebrides seismic zone. Note the anomalously large amount of active areas and the small amount of quiet areas in the asperities.



These tests can be done in the opposite direction by asking what portion of the asperities are also active or quiet. The distribution of quiet and active areas in the asperities is shown in the lower part of Figure 7. Thirty four percent of the asperity area is active as opposed to the 10% expected, and 6% of the asperity area is quiet as opposed to the 16% expected. This also indicates that asperities and active areas are related directly and that asperities and quiet regions are unrelated.

CHILE

The Mocha Block shows the highest level of background seismicity in all of Southern Chile (A1 in Figure 1). It is one of the truly outstanding features of the teleseismic seismicity of the subduction zones we examined. One cannot help but wonder, what is it about this segment of the interface between the Nazca and the South American plates which causes this intense concentration of seismicity.

The tectonic setting of the Mocha block is unique in South America. North of the block the seafloor was generated at the now extinct Pacific-Farallon spreading center [Handschumacher, 1976]. South of the block the seafloor was generated by the presently active East Pacific Rise. The transition between the two different seafloors occurs across the Mocha block. Furthermore, the Mocha block is rather small (100 km across), and is bounded on both sides by fracture zones (the Mocha (MFZ) on the north and the Valdivia (VFZ) on the south).

This unique tectonic setting of the Mocha block is interesting in itself but does not explain why the seismicity is so high. In order to understand this observation one must consider the details of the interface geometry in this region. Near the Mocha block this geometry is controlled by several features. The first is the depth differences across the fracture zones which bound the block. The second control on the interface geometry in this region is the position of the inactive Pacific-Farallon spreading center in the subducted Nazca plate. Handschumacher [1976] gives anomaly (and ridge) offsets for the fracture zones associated with the Pacific-Farallon spreading center. The MFZ has 500+ km of left-lateral offset. The position of the inactive ridge on the subducted plate is, therefore, 500+ km from the position of the ridge on the unsubducted Nazca plate north of the MFZ. In order to determine this position, we projected the MFZ and the relic ridge onto the seafloor south of the VFZ (Figure 8) and then measured the distance along the MFZ. The position of the relic ridge under the South American plate shown in Figure 8 is for 500 km of offset on the MFZ. It is, therefore, the westernmost possible position of the ridge according to the paleomagnetic evidence. This position bounds the area of high seismicity in the Mocha block on the west.

Cifuentes (1984) recently relocated the foreshocks and the mainshock of the great 1960 event which occurred in the Mocha Block using a master event technique. This technique improves the locations of the events relative to the location of the event selected as the master. The absolute locations of the events remain in error by the absolute error in the location of the master event. The improved epicenters of these events are shown in Figure 8. Note that they outline a linear feature with strike parallel to that expected for the relic spreading center (normal to the MFZ and the other fracture zones north of the Mocha Block). This alignment occurs along the eastern boundary of the region of high seismicity. Cifuentes also pointed out that these events show a clear migration pattern from the north end of the feature to the south.

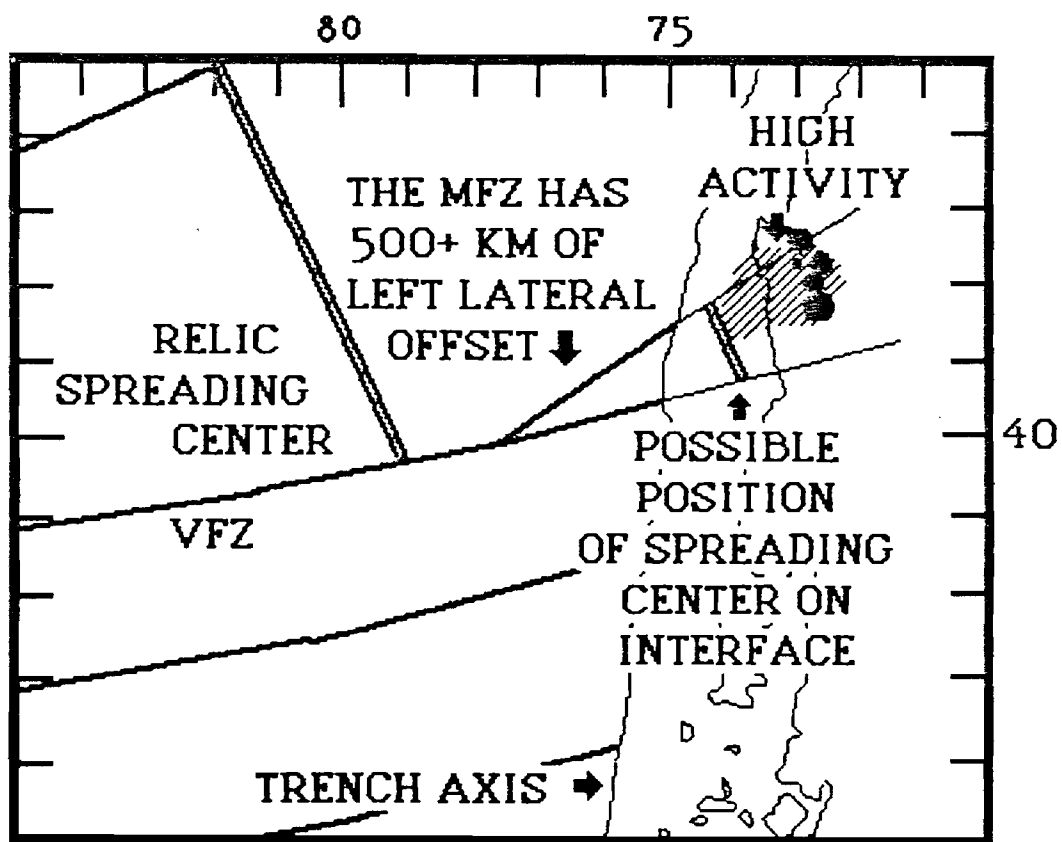


Figure 8. Geometry of the relic Pacific-Farallon spreading center in the Mocha Block region. The possible position of the spreading center on the interface is the westernmost possible position. The circles are the fore-shock sequence and the mainshock of the 1960 Chile event. These events are relocated relative to a central event in the sequence (Cifuentes, 1984). Note that the relative locations define a trend which is parallel to that of the relic spreading center. The fore-shocks migrated through time from the north to the south, where the mainshock occurred.

We proposed that the high seismicity in the Mocha Block is caused by interaction between the relic spreading center on the Nazca Plate and the South American Plate (Habermann, McCann, and Perin 1983, see Appendix I) on the basis of the paleomagnetic evidence. The seismological evidence of the linear feature associated with the 1960 foreshock sequence provides strong support for this proposal. The migration of the foreshock sequence suggests that it was made up of a series of ruptures along the interface between the relic spreading center and the overriding South American plate. The mainshock occurred near the southern end of this zone of interaction when the rupture front reached a simpler section of the interface and could rupture freely to the south.

COLUMBIA

Beck and Ruff (1984) recently published a detailed study of the asperity distribution associated with the great 1979 Columbia earthquake. An important finding of this study was the location of the major asperity for this event using directivity of the moment release function. They concluded that an asperity roughly 60 km long was responsible for a large majority of the seismic energy release of that event. The location of that asperity was between 2° and 2.5° N on the interface between the Nazca and South American plates. When one examines the most complete bathymetric data for this region, it is clear that the relic Malpelo spreading center enters the Colombian subduction zone at this location (Mendoza and Dewey (1984) misinterpreted the tectonic significance of the Yoquina Graben, a relic fracture zone which offsets the intersection of the ridge to the north). In fact, the aftershocks of the Colombian event show a clear lineation almost normal to the fault along this feature (see Beck and Ruff, Figure 3).

We examined the background seismicity in the region of the 1979 Columbia event as part of our study of the South American subduction zone. The region shows very low seismicity at the level we considered (5.1+) with large regions of no seismicity. A spatial cluster of five events of this size occurs near the intersection of the Malpelo rift and the subduction zone. No similar cluster occurs elsewhere along the northern South American subduction zone. The interpretation of this cluster is unclear because several of the events occurred following the 1979 event and may be late aftershocks. Further studies with relaxed magnitude cutoffs will clarify whether there is anomalously high seismicity in the region of the rift-subduction zone intersection.

SUMMARY

The cases presented here demonstrate the exciting potential of background seismicity for asperity recognition studies. The asperities in the New Hebrides are clearly more active than the other sections of the seismic zone. In the other two cases, asperities can be directly associated with features on the plate interfaces. Such associations are not rare on strike slip faults exposed at the surface, but these are the first of such recognized in subduction zone situations. More importantly, in each case the background seismicity contained information which could lead to recognition of these asperities prior to the mainshocks.